Testing the Reactor and Gallium Anomalies: The 4th ν Hypothesis

CERN Town Meeting
May 14th-16th 2012

Thierry Lasserre
CEA/DSM/Irfu
# Neutrino Anomalies & 4th Neutrino

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Source</th>
<th>Type</th>
<th>Sensitivity to Oscillation</th>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>Decay-at-Rest</td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>Total Rate, Energy</td>
<td>CC</td>
<td>3.8 $\sigma$</td>
</tr>
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<td>Short baseline</td>
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<td>Electron Capture</td>
<td>$\nu_e$ dis.</td>
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<td>Reactor</td>
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<td>Total Rate, Energy</td>
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<td>Big-Bang</td>
<td>All</td>
<td>Number of $\nu$, $N_{eff}$</td>
<td>CC</td>
<td>$\approx$2 $\sigma$</td>
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→ could be interpreted by an existing eV² 4th neutrino state...

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## Neutrino Anomalies & 4\textsuperscript{th} Neutrino

### this talk

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→ could be interpreted by an existing eV$^2$ 4\textsuperscript{th} neutrino state...

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The Gallium Neutrino Anomaly

- Tests of the solar neutrino detectors GALLEX and SAGE
- 4 calibration runs with intense ≈1 MCi neutrino sources
  - 2 runs at Gallex with a $^{51}$Cr source (750 keV $\nu_e$ emitter)
  - 1 run at SAGE with a $^{51}$Cr source
  - 1 run at SAGE with a $^{37}$Ar source (810 keV $\nu_e$ emitter)
- Observed/Expected Event Ratio: $R = 0.86 \pm 0.05$

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The Gallium Neutrino Anomaly

Fit to $\nu_e$ disappearance hypothesis (3+1)

$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos \theta_{\text{new}} & \sin \theta_{\text{new}} \\ -\sin \theta_{\text{new}} & \cos \theta_{\text{new}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_{\text{new}} \end{pmatrix}$$

$$P_{\nu_e \to \nu_e}(L, E) = 1 - \sin^2(2\theta_{\text{new}}) \sin^2 \left( \frac{\Delta m_{\text{new}}^2 L}{E} \right)$$

$\Delta m_{\text{new}}^2 \approx eV^2$

No-oscillation hypothesis disfavored at about 2.7$\sigma$
The Reactor Antineutrino Anomaly

2) Reanalysis 19 short Baseline Experiments Results, PRD83, 073006 (2011)

<table>
<thead>
<tr>
<th>result</th>
<th>Det. type</th>
<th>$\tau_n$ (s)</th>
<th>$^{235}$U</th>
<th>$^{239}$Pu</th>
<th>$^{238}$U</th>
<th>$^{241}$Pu</th>
<th>old</th>
<th>new</th>
<th>err(%)</th>
<th>corr(%)</th>
<th>L(m)</th>
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<tbody>
<tr>
<td>Bugey-4</td>
<td>$^3$He+H$_2$O</td>
<td>888.7</td>
<td>0.538</td>
<td>0.328</td>
<td>0.078</td>
<td>0.056</td>
<td>0.987</td>
<td>0.926</td>
<td>3.0</td>
<td>3.0</td>
<td>15</td>
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<tr>
<td>ROVNO91</td>
<td>$^3$He+H$_2$O</td>
<td>888.6</td>
<td>0.614</td>
<td>0.274</td>
<td>0.074</td>
<td>0.038</td>
<td>0.985</td>
<td>0.924</td>
<td>3.9</td>
<td>3.0</td>
<td>18</td>
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<tr>
<td>Bugey-3-I</td>
<td>$^6$Li-LS</td>
<td>889</td>
<td>0.538</td>
<td>0.328</td>
<td>0.078</td>
<td>0.056</td>
<td>0.988</td>
<td>0.930</td>
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<tr>
<td>Bugey-3-II</td>
<td>$^6$Li-LS</td>
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<td>0.538</td>
<td>0.328</td>
<td>0.078</td>
<td>0.056</td>
<td>0.994</td>
<td>0.936</td>
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<td>0.620</td>
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<td>0.042</td>
<td>1.018</td>
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<td>Goesgen-II</td>
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<td>0.543</td>
<td>0.329</td>
<td>0.070</td>
<td>0.058</td>
<td>0.975</td>
<td>0.909</td>
<td>7.6</td>
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<tr>
<td>ILL</td>
<td>$^3$He+LS</td>
<td>889</td>
<td>$\approx$ 1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.832</td>
<td>0.788</td>
<td>9.5</td>
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<tr>
<td>Krasn. I</td>
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<td>—</td>
<td>—</td>
<td>1.013</td>
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<td>—</td>
<td>—</td>
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<tr>
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<td>—</td>
<td>0.987</td>
<td>0.936</td>
<td>3.7</td>
<td>3.7</td>
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<tr>
<td>SRP II</td>
<td>Gd-LS</td>
<td>887</td>
<td>$\approx$ 1</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>0.042</td>
<td>0.969</td>
<td>0.901</td>
<td>6.9</td>
<td>6.9</td>
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<td>0.076</td>
<td>0.045</td>
<td>1.001</td>
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<td>0.274</td>
<td>0.074</td>
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<td>0.990</td>
<td>0.922</td>
<td>7.2</td>
<td>7.2</td>
<td>18</td>
</tr>
</tbody>
</table>
The Reactor Antineutrino Anomaly

- Observed/predicted averaged event ratio: $R = 0.927 \pm 0.023$
  - i) Improved reactor neutrino spectra
  - ii) Reevaluation of IBD cross sections (neutron life time @878 s)
  - iii) Accounting for long-lived radioisotopes accumulating in reactors
- $3.0 \sigma$ deviation with respect to $R=1$ (rate only)

Experiments measured a $\nu_e$ deficit

Terra Incognita

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The Reactor Antineutrino Anomaly

Rate Only Analysis

- Best $\Delta m^2$ fit value shifts upward when including the Bugey-3 energy spectrum

Rate + Shape Only Analysis

- Bugey-3 did not observe energy spectrum distortion (but large PWR core extension)

- Puzzling ILL results (only experiment <10m from compact core)
Combining Gallium & Reactor Anomalies

No-oscillation hypothesis disfavored at 3.6σ

\[ \Delta m^2_{\text{new}} \approx eV^2 \]

\[ \sin^2(2\theta_{ee}) \approx 0.1 \]
Synthesis of reactor $\nu$ oscillations

- New short-baseline neutrino oscillation experiments are needed

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### 4th-V Reactor Proposal Overview

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Reactor</th>
<th>Fuel (#fissions)</th>
<th>Core Size (m)</th>
<th>$&lt;L&gt;$ (m)</th>
<th>Depth (mwe)</th>
<th>Status</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucifer Saclay</td>
<td>Osiris</td>
<td>$^{235}\text{U}$</td>
<td>&lt;1</td>
<td>7</td>
<td>5</td>
<td>Data Taking</td>
<td>Non proliferation $1 \text{ m}^3 \text{ Gd-LS}$ Mostly Rate + Shape?</td>
</tr>
<tr>
<td>Stereo Genoble</td>
<td>ILL</td>
<td>$^{235}\text{U}$</td>
<td>&lt;1</td>
<td>10</td>
<td>10</td>
<td>Proposal</td>
<td>2 $\text{ m}^3 \text{ Gd-LS}$ Rate + Mostly shape</td>
</tr>
<tr>
<td>SCRAMM (CA)</td>
<td>San-Onofre</td>
<td>$^{235,238}\text{U}$, $^{239,241}\text{Pu}$</td>
<td>3x3.8</td>
<td>24</td>
<td>30</td>
<td>Proposal</td>
<td>2 $\text{ m}^3 \text{ Gd-LS}$ Mostly Rate + Shape</td>
</tr>
<tr>
<td>SCRAMM (Idaho)</td>
<td>ATR</td>
<td>$^{235}\text{U}$</td>
<td>&lt;1</td>
<td>12</td>
<td>15</td>
<td>Proposal</td>
<td>2 $\text{ m}^3 \text{ Gd-LS}$ Rate + Mostly shape</td>
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<tr>
<td>DANSS (Russia)</td>
<td>KNPP</td>
<td>$^{235,238}\text{U}$, $^{239,241}\text{Pu}$</td>
<td>few</td>
<td>14</td>
<td>70</td>
<td>Being Built</td>
<td>Segmented detector $1 \text{ m}^3$ Rate + Shape?</td>
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<tr>
<td>NIST (US)</td>
<td>NCNR</td>
<td>$^{235}\text{U}$</td>
<td>$\approx$1</td>
<td>4-11</td>
<td>0</td>
<td>Proposal</td>
<td>Rate + Mostly shape</td>
</tr>
</tbody>
</table>
Nucifer, Osiris (Saclay)

- First goal: Non Proliferation: $P_{th}$ & Fuel Composition U/Pu
- Osiris Site in Saclay
  - 70 MW Research reactor, size: 57x57x60 cm
  - Detector Size: 1.2x0.7m (850l)
  - Shallow Depth: 5 m.w.e
  - $<L>=7.0\pm0.3$ m $\rightarrow$ high gamma ray flux

- Status: start taking data - Commissioning
  - Scintillator upgrade
  - $\gamma$-ray Shielding upgrade
The SCRAAM Proposal (LLNL)

- **Detector**
  - 2 tons Gd-LS
  - 150 days,
  - 4% Normalization
  - 1.5% $\varepsilon_{\text{scale}}$
  - S/N = 8/1

- **Site 1: extended core**
  - SONGS: 3 GW PWR
  - 24 m baseline

- **Site 2: compact core**
  - ATR 150 MW research reactor
  - 12 m baseline

- **Sensitivity (99%, shape-only)**
Stereo, ILL (courtesy D. Lhuillier)

Search for a new oscillation pattern few meters away from a compact core

- 1x1x2 m target vessel filled with Gd-doped LS
- 5 baseline bins materialized by diffusive foils
- Simple and safe readout from top
- Side g catcher for better resolution and $e_n$ (55%)
- Full coverage of CH2 and Pb shielding + top muon veto

Investigating a new potential site @ ILL research reactor
- Saclay
- TU Munich
- LAPP

- Phase shift of the $E$ oscillation pattern along the detector axis $\rightarrow$ extra control of the background subtraction

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Stereo, ILL (courtesy D. Lhuillier)

- 300 days, 50 W, $L_0 = 8$ m
- $S/B = 1.5$
- Threshold $E_{\text{vis}} > 2$ MeV
- Neutron cut = 6 MeV
- 5 baseline bins of 40 cm
- Complete det. Response (Geant4)
- 2% $E$ scale + error budget of predicted spectra
- $\sim 700 \overline{\nu}/d$

→ Do NOT rely on Reactor Flux Prediction
→ Cover the reactor antineutrino anomaly parameter space

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Oscillometry inside a $\nu$-detector

- Place the $\nu$-emitter inside or close to existing detectors
  - Very short Baseline
  - Low Background
- $\nu$-source at center
  \[
  \frac{dN_{\nu}}{dR} \propto \left[ 1 - \sin^2(2\theta) \sin^2\left(1.27 \frac{\Delta m^2 R}{\langle E \rangle}\right) \right]
  \]
- $\nu$-source Outside
  - Complex but specific oscillation pattern - Modest solid angle

$\nu$-emitter
$\nu$-detector $\varnothing=13 \text{ m}$

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### V-source Proposal Overview

<table>
<thead>
<tr>
<th>Type</th>
<th>channel</th>
<th>Background</th>
<th>Source</th>
<th>Production</th>
<th>Activity (Mci)</th>
<th>Proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$\nu_e e \rightarrow \nu_e e$</td>
<td>Compton edge (irreducible)</td>
<td>$^{51}$Cr</td>
<td>$n_{th}$ irradiation in Reactor</td>
<td>in</td>
<td>&gt;3</td>
</tr>
<tr>
<td></td>
<td>5% $E_{res}$</td>
<td>$\nu$ -Source (out ok but in ?)</td>
<td>0.75 MeV</td>
<td>26d</td>
<td>out</td>
<td>5-10</td>
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<tr>
<td>$\bar{\nu}_e$</td>
<td>$\bar{\nu}_e p \rightarrow e^+ n$</td>
<td>reactor $\nu$ &amp; $\nu$ -Source</td>
<td>$^{37}$Ar</td>
<td>$n_{fast}$ irradiation in Reactor (breeder)</td>
<td>in</td>
<td>&gt;1</td>
</tr>
<tr>
<td></td>
<td>$E_{th}=1.8$ MeV</td>
<td>$e^+ n$ (e$^+$,n) Coincidence</td>
<td>0.8 MeV</td>
<td>35d</td>
<td>out</td>
<td>5</td>
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<tr>
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<td>5% $E_{res}$</td>
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<td>$^{144}$Ce</td>
<td>spent nuclear fuel reprocessing</td>
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<td>0.005-0.05</td>
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<td></td>
<td>15cm $R_{res}$</td>
<td>Background free!</td>
<td>$^{90}$Sr</td>
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<td>$^{106}$Rh</td>
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<td>$^{42}$Ar</td>
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</tr>
</tbody>
</table>

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3 Mci $^{51}$Cr Source at Baksan

- Produce 3.5 kg of enriched $^{50}$Cr (97%) and irradiation to 3 Mci

- Deploy in a new dual Metallic Ga Target at Baksan (4700 mwe)
  - 9 days exposure
  - $^{71}$Ge extraction
  - $^{51}$Cr activity measurement
  - Start new cycle

- Analyze ratio of measured capture rates to predicted rate in inner and outer zones and their ratio $R_2/R_1$

- Not sensitive to $\gamma$-ray background
Comment on $\nu_e$ sources in LAND

- A strong $^{37}$Ar 1 Mci $\nu$ source at the center of a large LS detector
- Elastic scattering on $e^-$ (few 10000 evts, 150 days, $E>250$ keV)
- Irreducible Backgrounds: $^7$Be Solar Neutrinos!

- Large S/N $\rightarrow$ Need few Mci $^{37}$Ar source inside
- Challenging deployment of $^{51}$Cr inside (outside OK see Borexino talk)

$$\Delta m^2_{\text{new}} = 2 \text{eV}^2 \text{ and } \sin^2(2\theta_{\text{new}})=0.1$$
## V-source Proposal Overview

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<td>Baksan LENS</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>out</td>
<td>Borexino SNO+</td>
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<tr>
<td></td>
<td>$5% E_{res}$</td>
<td>Solar $\nu$ (irreducible)</td>
<td>$^{37}\text{Ar}$</td>
<td>$n_{fast}$ irradiation in Reactor (breeder)</td>
<td>in</td>
<td>Ricochet (NC)</td>
</tr>
<tr>
<td></td>
<td>$15\text{cm } R_{res}$</td>
<td>$\nu$ -Source (out ok but in ?)</td>
<td></td>
<td></td>
<td>out</td>
<td></td>
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<tr>
<td>$\bar{\nu}_e$</td>
<td>$\bar{\nu}_e p \rightarrow e^+ n$</td>
<td>reactor $\nu$ &amp; $\nu$ -Source</td>
<td>$^{144}\text{Ce}$</td>
<td>spent nuclear fuel reprocessing</td>
<td>in</td>
<td>CeLAND Borexino</td>
</tr>
<tr>
<td></td>
<td>$E_{th}=1.8 \text{ MeV}$</td>
<td></td>
<td></td>
<td></td>
<td>out</td>
<td>Daya-Bay</td>
</tr>
<tr>
<td></td>
<td>$(e^+,n)$</td>
<td></td>
<td>$^{90}\text{Sr}$</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Coincidence</td>
<td></td>
<td>$^{106}\text{Rh}$</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>$5% E_{res}$</td>
<td></td>
<td>$^{42}\text{Ar}$</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>$15\text{cm } R_{res}$</td>
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</tbody>
</table>

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- acrylics/nylon sphere: R=6.5 m
- Chimney: R>0.5 m
- Suspension System
- Antineutrino Generator (R=4cm) & Passive Shielding (R=40 cm)
**Antineutrino Source: $^{144}\text{Ce}-^{144}\text{Pr}$**

(*ITEP N°90 1994, PRL 107, 201801, (2011)*)

- **1\textsuperscript{st} Trick:** $\bar{\nu}_e$ source detected via $\bar{\nu}_e + p \rightarrow e^+ + n$ (Thr=1.8 MeV)
  - High cross section $\rightarrow$ need (only) kCi activity $\rightarrow$ Compactness
  - $(e^+, n)$ detected in coincidence $\rightarrow$ Background free experiment

- **2\textsuperscript{nd} Trick:** $^{144}\text{Ce}-^{144}\text{Pr}$
  - Abundant fission product
  - $^{144}\text{Ce}$: long-lived & low-$Q_\beta$
    $\rightarrow$ Enough time to produce, transport, use
  - $^{144}\text{Pr}$: short-lived & high-$Q_\beta$
    $\rightarrow$ $\bar{\nu}_e$-emitter above threshold
50 kCi $^{144}$Ce-$^{144}$Pr Source & Shield

- Produce a pure source of 50 kCi (2.10$^{15}$ Bq) of $^{144}$Ce
  - Standard reprocessing of 1 ton of spent nuclear fuel
  - Extraction of rare earths
  - Separation of Ce by chromatography
  - Need low level $\gamma$-rays or $n$ emitter

- $^{144}$Pr emits gamma rays
  - 2.185 MeV $\gamma$ - 0.7% branching ratio
  - 10$^{-12}$ attenuation needed

- Tungsten Shielding (r=42 cm, 5 tons)
  - 33 cm thickness (18.5 g/cm$^3$)
  - Radiopure (mBq/kg), compatible with oil
CeLAND in KamLAND

- Integration Constraints
  - Radiopurity / Cleanliness
    - Ultra-pure detector
    - Scintillator transparency (>10m)
  - Mechanical
    - 5 ton W-shield (7 pieces)
    - Chimney Ø=55 cm
  - Thermal
    - 50 kCi $^{144}$Ce release 200 W
- Data Taking in 2016?
CeLAND: Signal & Background

144Ce-144Pe Emitter Induced Backgrounds

Other Backgrounds

Event rate (in 10 cm radius bins)

Radius R (m)

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CeLAND Expected Signal (Oscillation)

\[
\frac{d^2 N(R, E_\nu)}{dR dE_\nu} = A_0 \cdot n \cdot \sigma(E_\nu) \cdot S(E_\nu) \cdot P(R, E_\nu) \int_0^{t_e} e^{-t/\tau} dt,
\]

Specific energy \((E, R)\) oscillation signatures

Measurement of the oscillation parameters

\[^{144}Pr\bar{\nu}_e\text{-spectrum}\]

Oscillation imprinted inside the detector

\(E_{\text{vis}}\) (MeV)

Energy Spectrum Distortion

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CeLAND: Sensitivity

50 kCi $^{144}$Ce-$^{144}$Pr – 1 year of data

$\Delta m^2_{\text{new}}$ (eV$^2$) vs $\sin^2(2\theta_{\text{new}})$

95% C.L. exclusion

3$\sigma$ measurement

$^{144}$Ce – 50 kCi – 1 y – W/Cu shield: 30/5cm, 95% CL
Same as solid curve but shape only
Reactor $\nu$ anomaly, PRD 83 073006 (2011), 95% CL
Reactor $\nu$ anomaly, PRD 83 073006 (2011), 90% CL

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**144Ce-144Pr Proposals**

3 Suitable Detectors (may necessitate mechanical upgrades)

Another proposal: a 500 kCi $^{144}$Ce-$^{144}$Pr source in Daya Bay

(D.A. Dwyer et al., arXiv:1109.6036)

500 kCi $^{144}$Ce-$^{144}$Pr source

see Borexino's Talk
500 kCi $^{144}$Ce-$^{144}$Pr in Daya Bay

- 500 kCi of $^{144}$Ce in the water pool of the Daya Bay far hall
- Source outside
  - Loose symmetry & $\nu$'s (more complex pattern)
  - but easier to deploy
  - $\gamma$'s attenuated in water
- Multiple source location to probe sterile oscillations
- Sensitivity to the RAA+GAA
Comparison of proposal sensitivities

Contours comparison (95 % CL, 2 dof)

Compilation: G. Mention

RAA
Ce–LAND rate & shape
Ce–LAND shape only
Borexino Ce
Borexino Cr
SAGE 2
Ricochet
LENS–Sterile
Cern–LAr
SNO+ Cr
Daya Bay Ce (500 kCi)
STEREO

Data From
Sterile Neutrino White Paper

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Conclusion & Outlook

- Test of both Reactor & Gallium Anomalies needs Energy and baseline-dependent signatures for an unambiguous resolution

- 3 complementary approaches with ≠ systematics
  - Measurements very close (<15m) to compact nuclear reactor
    - DANSS, NIST, SCRAAM, STERE0, ... : 5 y time scale – few M€
  - Measurements with (anti-)neutrino emitters (10 kCi→10 MCi)
    - Basksan, Borexino, CeLAND, DayaBay, LENS, 5 y time scale – few M€
  - Accelerator based short baseline proposals
    - Based on Lar detectors @CERN & Fermilab
    - Test of the LSND anomaly
    - Test of the RAA+GA anomaly with ≠L & ≠E → oscillation


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Thanks for your attention!
Additional Slides
List of Proposals

- Pion & Kaon Decay In Flight Beams (CERN, Fermilab)
  - Microboone, ICARUS/NESSIE, LArLAr, Nova-NearDet

- Stopped Pion Beams
  - OscSNS

- Short Baseline Reactor Experiments (Beta-decay)
  - Nucifer, SCRAAM, DANSS, Stereo, Poseidon

- Neutrino Generator Experiment (Electron Capture)
  - $^{51}$Cr proposals: Borexino, SNO+, Baksan,

- Anti-Neutrino Generator Experiment (Beta-decay)
  - $^{144}$Ce proposals: Ce-LAND in KamLAND/Borexino, Daya Bay
4th Neutrino $\rightarrow$ Sterile

- **Status:** 3 active neutrinos $\nu_e$, $\nu_\mu$, $\nu_\tau$
  - 2 independent $\Delta m^2$ (solar $8 \times 10^{-5}$ eV$^2$ and atmo $2 \times 10^{-3}$ eV$^2$)

- **Why a 4th neutrino?**
  - Oscillation implying a new mass scale, $\Delta m^2 \approx 1$ eV$^2$

- **Why Sterile?**
  - LEP invisible Z-width measurement, $N_{\text{light-active}} = 3$
  - No (or weak) coupling with the Z & W bosons

- **What about theory?**
  - Most $m_\nu$ models involve sterile neutrinos
    - Add right-handed neutrinos also called ‘Sterile’ $\nu_S$
  - BUT mass anywhere from sub-eV to $10^{19}$ GeV
  - Active $\nu_e$, $\nu_\mu$, $\nu_\tau$ can mix with sterile $\nu_S$

- **Observable?**
  - disappearance of active neutrinos
Main Anomalous Physics Channels

- LSND Anomaly / Miniboone (no conclusive):
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ & expect ‘small’ mixing angle $\theta_{\mu e}$

- Reactor Anomaly:
  - $\bar{\nu}_e \rightarrow \bar{\nu}_e$ & expect ‘large’ mixing angle $\theta_{ee}$

- Gallium Anomaly:
  - $\nu_e \rightarrow \nu_e$ & expect ‘large’ mixing angle $\theta_{ee}$

- Cosmology: Constraint Effective Number of Degrees of freedom, $N_{\text{eff}} > 3$, in the Universe (not necessarily neutrinos)

- But no precise measurement of:
  - $\nu_\mu \rightarrow \nu_\mu$ & expect ‘large’ mixing angle $\theta_{\mu \mu}$
**'4th Neutrino' Astrophysical Indications**

Universe Expansion Rate \( H^2 \approx (\rho_\gamma + \rho_\nu) \) \( \rho_\gamma \) given by CMB data

<table>
<thead>
<tr>
<th>Model</th>
<th>Data</th>
<th>( N_{\text{eff}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{eff}} )</td>
<td>W-5+BAO+SN+H(_0)</td>
<td>4.12(^{+0.87}<em>{-0.85})(^{+1.76}</em>{-1.63})</td>
</tr>
<tr>
<td></td>
<td>W-5+LRG+H(_0)</td>
<td>4.10(^{+0.76}<em>{-0.77})(^{+1.60}</em>{-1.43})</td>
</tr>
<tr>
<td></td>
<td>W-5+CMB+BAO+XLF+( f_{\text{gas}} )+H(_0)</td>
<td>3.4(^{+0.5}_{-0.6})</td>
</tr>
<tr>
<td></td>
<td>W-5+LRG+maxBCG+H(_0)</td>
<td>3.77(^{+0.67}<em>{-0.67})(^{+1.37}</em>{-1.24})</td>
</tr>
<tr>
<td></td>
<td>W-7+BAO+H(_0)</td>
<td>4.34(^{+0.86}_{-0.88})</td>
</tr>
<tr>
<td></td>
<td>W-7+LRG+H(_0)</td>
<td>4.25(^{+0.76}_{-0.80})</td>
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<tr>
<td></td>
<td>W-7+ACT</td>
<td>5.3 \pm 1.3</td>
</tr>
<tr>
<td></td>
<td>W-7+ACT+BAO+H(_0)</td>
<td>4.56 \pm 0.75</td>
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<tr>
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<td>W-7+SPT</td>
<td>3.85 \pm 0.62</td>
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<tr>
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<td>W-7+SPT+BAO+H(_0)</td>
<td>3.85 \pm 0.42</td>
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<td>W-7+ACT+SP+LRG+H(_0)</td>
<td>4.08(^{+0.71}_{-0.68})</td>
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<td>W-7+ACT+SP+BAO+H(_0)</td>
<td>3.89 \pm 0.41</td>
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\[ N_{\text{eff}} + f_\nu \]

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{eff}} + f_\nu )</td>
<td>W-7+CMB+BAO+H(_0)</td>
<td>4.47(^{+1.82}<em>{-1.74}) (^{+1.22}</em>{-1.25})</td>
</tr>
<tr>
<td></td>
<td>W-7+CMB+LRG+H(_0)</td>
<td>4.8(^{+1.86}_{-1.75})</td>
</tr>
</tbody>
</table>

\[ N_{\text{eff}} + \Omega_k \]

<table>
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<tr>
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<th>( N_{\text{eff}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{eff}} + \Omega_k )</td>
<td>W-7+BAO+H(_0)</td>
<td>4.61 \pm 0.96</td>
</tr>
<tr>
<td></td>
<td>W-7+ACT+SP+BAO+H(_0)</td>
<td>4.03 \pm 0.45</td>
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</table>

\[ N_{\text{eff}} + \Omega_k + f_\nu \]

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</thead>
<tbody>
<tr>
<td>( N_{\text{eff}} + \Omega_k + f_\nu )</td>
<td>W-7+ACT+SP+BAO+H(_0)</td>
<td>4.00 \pm 0.43</td>
</tr>
</tbody>
</table>

\[ N_{\text{eff}} + \Omega_k + f_\nu + w \]

<table>
<thead>
<tr>
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<th>( N_{\text{eff}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{eff}} + \Omega_k + f_\nu + w )</td>
<td>W-7+CMB+BAO+H(_0)</td>
<td>3.68(^{+1.90}<em>{-1.84}) (^{+2.02}</em>{-2.02})</td>
</tr>
<tr>
<td></td>
<td>W-7+CMB+LRG+H(_0)</td>
<td>4.8(^{+1.90}<em>{-1.84}) (^{+2.02}</em>{-2.02})</td>
</tr>
</tbody>
</table>

\[ N_{\text{eff}} + \Omega_k + f_\nu + w + \eta_\gamma \]

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{eff}} + \Omega_k + f_\nu + w + \eta_\gamma )</td>
<td>W-7+CMB+BAO+SN+H(_0)</td>
<td>4.2(^{+1.10}<em>{-0.61})(^{+2.00}</em>{-1.14})</td>
</tr>
<tr>
<td></td>
<td>W-7+CMB+LRG+SN+H(_0)</td>
<td>4.3(^{+1.40}<em>{-0.54})(^{+2.30}</em>{-1.09})</td>
</tr>
</tbody>
</table>

CMB data \( N_{\text{eff}} \) > 3 (2\( \sigma \))
An Unambiguous Proof of $\nu_e \rightarrow \nu_s$ Oscillation

$$\frac{dN}{dR}(R,t) \propto \frac{A(t)}{4\pi R^2} \times \langle \sigma \rangle \times N_p \times 4\pi R^2 \times P_{ee} \left( \frac{\Delta m^2 R}{\langle E \rangle} \right)$$

144Ce (50 kCi – 1 y) Neutrino Generator

Detector Center

Analysis Energy Region
The ILL Neutrino Experiment (1981)

- 1st reactor neutrino program in Europe at the ILL, Research Reactor, Grenoble, 80-81 (TUM)

- Channel: $\text{anti-}\nu_e \rightarrow \text{anti-}\nu_e$

- Detection: $\text{anti-}\nu_e + p \rightarrow e^+ + n$

- Baseline: 8.8 m

- Energy: 1-8 MeV

- Results:
  - 1980: $R = 0.95 \pm 0.1$ $\rightarrow$ consistent with no-oscillation
  - BUT hint of spectrum distortion consistent with $eV^2$ oscillations (1980...)
  - Epilogue: Reevaluation of the reactor power by +10% in 1995
    $\rightarrow$ observed/predicted measured ratio $R = 0.8 \pm 0.1$ ($2\sigma$ anomaly)
LSND (Los Alamos)

- 1st results published in PRL 75 (1995)
- Channel: anti-ν_μ \rightarrow anti-ν_e
- Detection: anti-ν_e + ^1H \rightarrow e^+ + n
- Baseline: 30 m
- Energy: 20 < E (MeV) < 200
- Status:
  - anti-ν_e apparition observed
  - not confirmed by Karmen
- Oscillation parameters:
  - Δm^2 >> 0.2 eV^2 >> Δm_{atm}^2 >> Δm_{sol}^2
  - Require a fourth (sterile) neutrino state
Miniboone Neutrino (FNAL)

- 1st results published in PRL 98 (2007)
- Channel: $\nu_\mu \rightarrow \nu_e$
- Detection: $\nu_e n \rightarrow e^+ p$ (CCQE)
- Baseline: 541 m
- Energy:
  - $475 < E$ (MeV) $< 3000$
  - Oscillation window $E > 475$ MeV
- Status:
  - LSND not confirmed ($E > 475$ MeV)
  - Excess of event at low energy, not consistent with neutrino oscillation (Under investigation)
Miniboone Antineutrino

- 1\textsuperscript{st} results published in PRL 103 (2009)
  - new result in July 2011

- Channel: anti-$\nu_\mu \rightarrow$ anti-$\nu_e$

- Detection: anti-$\nu_e + \text{^1H} \rightarrow \text{e}^+ + \text{n}, \text{FNAL}$

- Baseline: 541 m

- Energy:
  - 200 < $E$ (MeV) < 1250
  - Oscillation window $E$ > 475 MeV

- Status:
  - 2.3$\sigma$ excess in/out the oscillation window
  - Inconclusive
    - Consistent with LSND
    - But also consistent with no oscillation